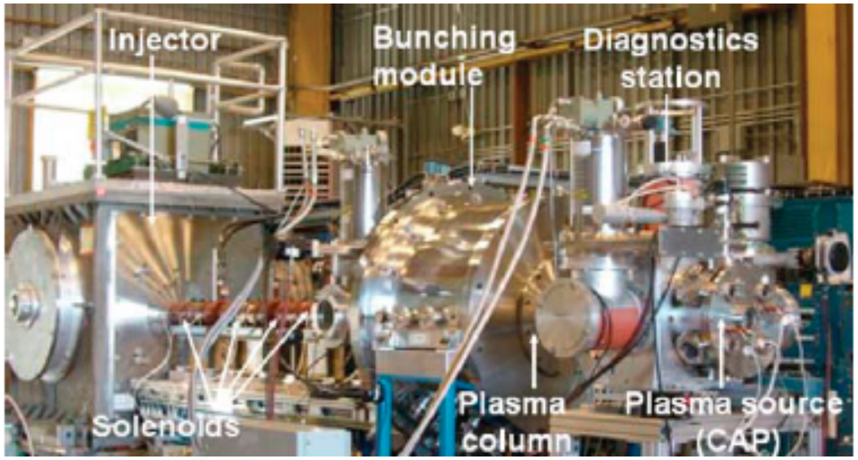
Beam Physics for WDM

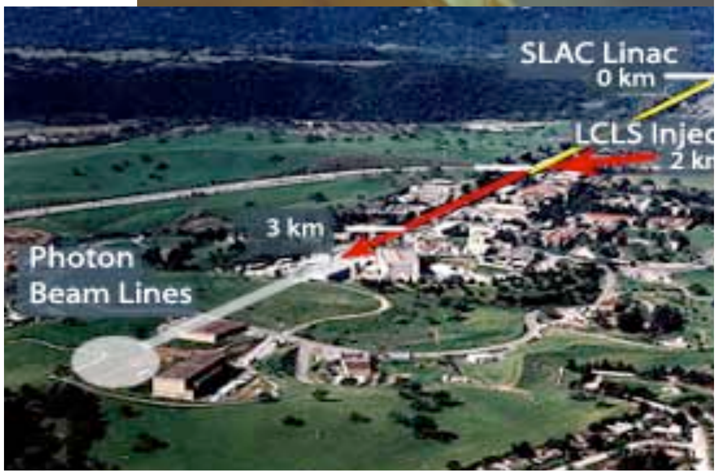
Warm Dense Matter Winter School

January 15, 2008

Jonathan Wurtele

UC Berkeley and LBNL



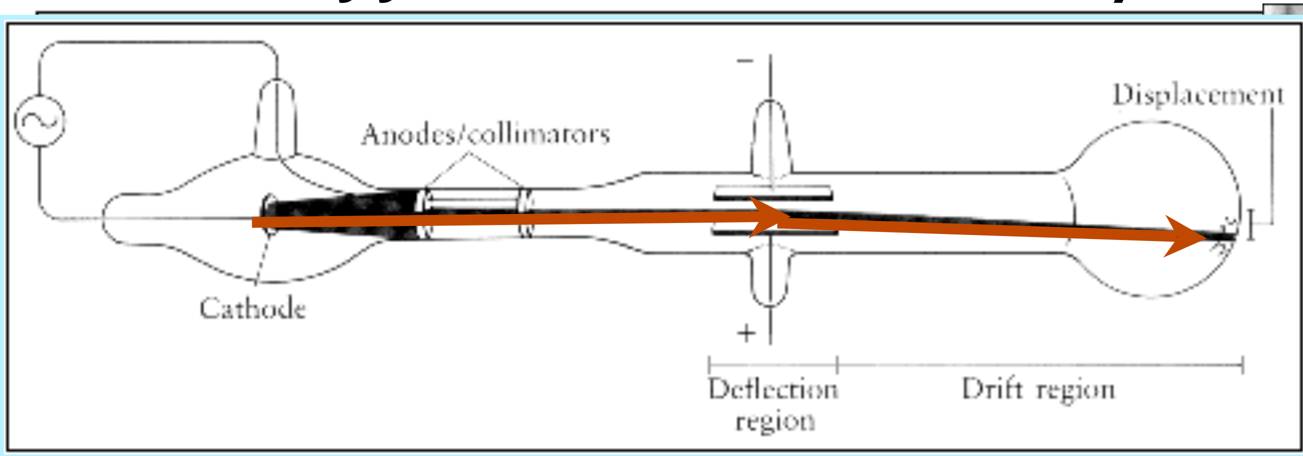


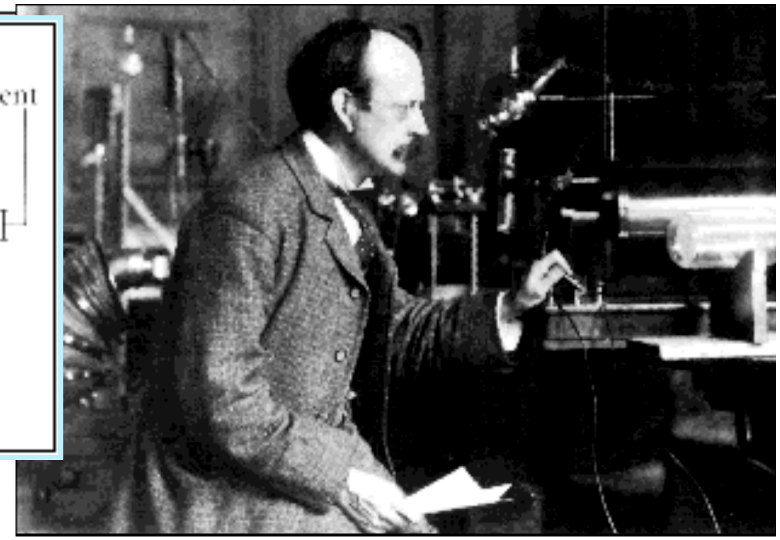
How Accelerators Work

Magnetic and electric fields focus and deflect particles

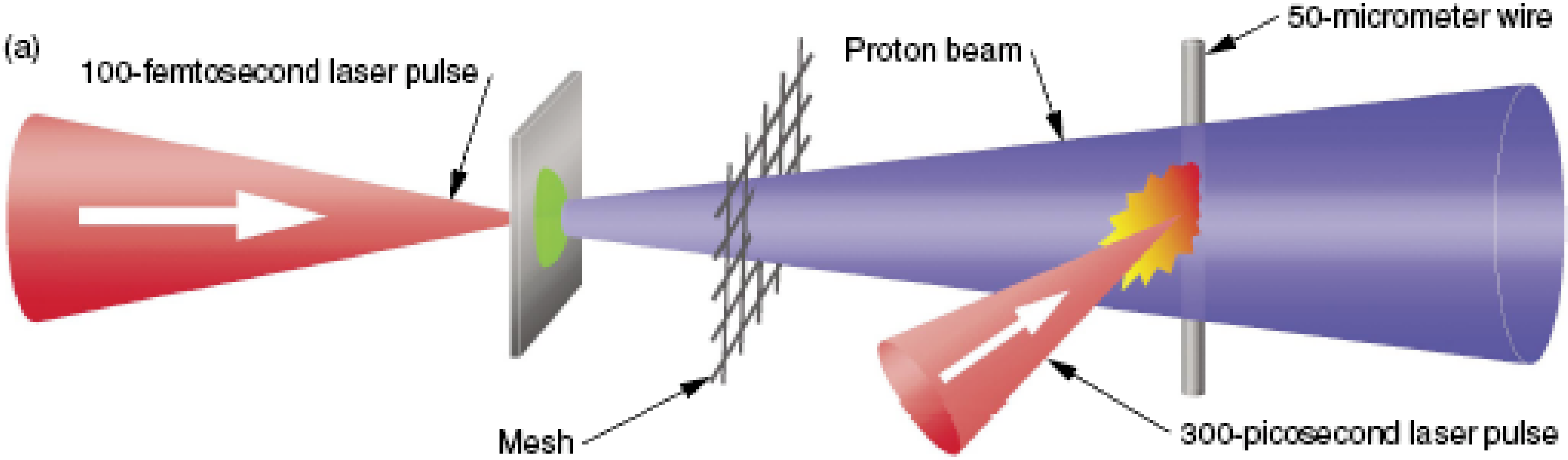
Electric fields accelerate particles

J.J. Thomson: discovery of the electron





Laser-solid ion accelerator

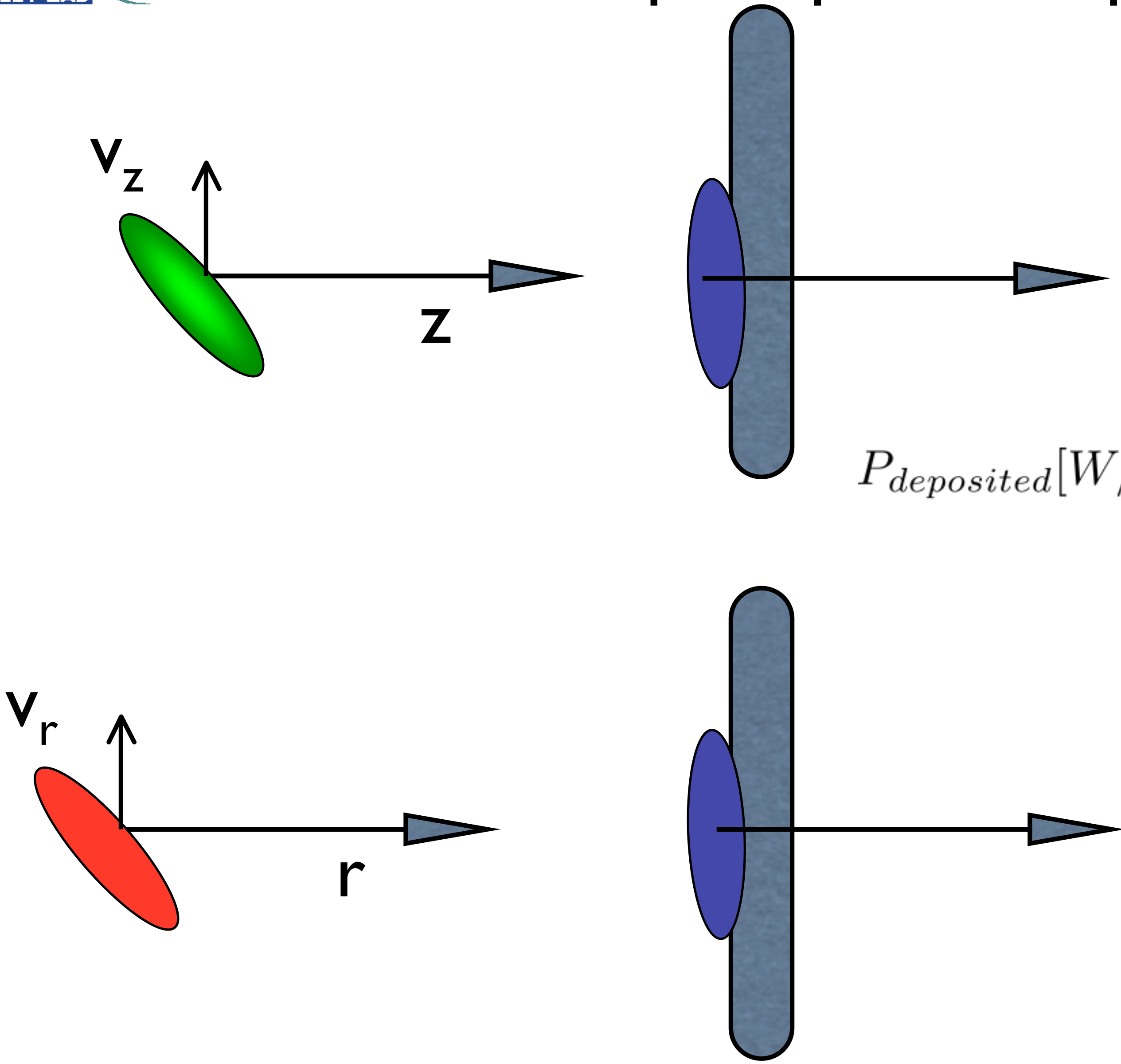


LULI

Outline

- Overview
- Ion beams
- Electron beams and X-ray FELs
- Plasma-based accelerators

3D focus for peak power deposition



$$
\begin{aligned}
P_{deposited}[W/kg] &= \frac{E_{deposited}}{\tau} \\
&= \frac{(N_{ion}\frac{dE}{dz}L_{target})}{\tau\pi R_{beam}^2 L_{target}\rho_{tar}} \\
&= \left(\frac{1}{\rho_t}\frac{dE}{dz}\right)\left(\frac{N_i}{\pi R_b^2 \tau}\right)
\end{aligned}
$$

Code: green is longitudinal phase space,
red is transverse phase space, blue is r-z space

The equations may be written in Lagrangian form

Convective derivative: $\frac{d}{dt} = \frac{\partial}{\partial t} + v \cdot \nabla$

Mass conservation equation: $\frac{d\rho}{dt} = -\rho \; \nabla \cdot v$

Acceleration equation $\rho \frac{dv}{dt} = - \; \nabla p$

Adiabatic flow condition: $\rho \frac{ds}{dt} = \rho \boxed{\dot{s}_{source}}$

In Lagrangian form, the energy conservation equation reads:

$$\frac{d}{dt}\left(\rho\varepsilon + \frac{1}{2}\rho v^2\right) = -\nabla \cdot (pv) - \left(\rho\varepsilon + \frac{1}{2}\rho v^2\right) \nabla \cdot v \; + \; \rho \boxed{\dot{\varepsilon}_{source}}$$

Beam Brightness

$$B_n = \frac{N}{V_{6d}}$$

$$\underbrace{V_{6d}}_{\text{6d phase space}} = \underbrace{\epsilon_{n\|}}_{\text{2d longitudinal phase space}} \underbrace{\epsilon_{n\perp}^2}_{\text{4d perpendicular phase space}}$$

$$\frac{N}{\pi R_b^2 \tau} \propto B_n \frac{\epsilon_{n\perp}}{\beta} \delta E$$

$$\boxed{\begin{aligned} P_{deposited}[W/kg] &= \frac{E_{deposited}}{\tau} \\ &= \frac{(N_{ion}\frac{dE}{dz}L_{target})}{\tau\pi R_{beam}^2 L_{target}\rho_{target}} \\ &= \left(\frac{1}{\rho_t}\frac{dE}{dz}\right)\left(\frac{N_i}{\pi R_b^2 \tau}\right) \end{aligned}}$$

B is invariant (technology and physics limits)

β is focusing (technology)

Energy spread limited by target, chromatic defocusing, etc

A goal for beam drivers: heat target to ~1eV quickl (little hydro expansion)

Time scale set by L/v where L is target dimension

X-ray drivers can penetrate for bulk heating

Laser drivers are absorbed in a skin depth (at low power)

Desired laser energy/pulse is not (now) hard to obtain

Intense charged particle beams are hard to obtain
Charged particle beams tend to self-destruct.

Envelope Equation

R=radius of beam

$$\frac{d^2 R}{dz^2} + \underbrace{\kappa^2 R}_{\text{focusing}} = \underbrace{\frac{I}{I_A \gamma^3 R}}_{\text{Space charge}} + \underbrace{\frac{\epsilon_\perp^2}{R^3 \gamma^2}}_{\text{pressure}}$$

Current neutralization eliminates (or reduces) space charg

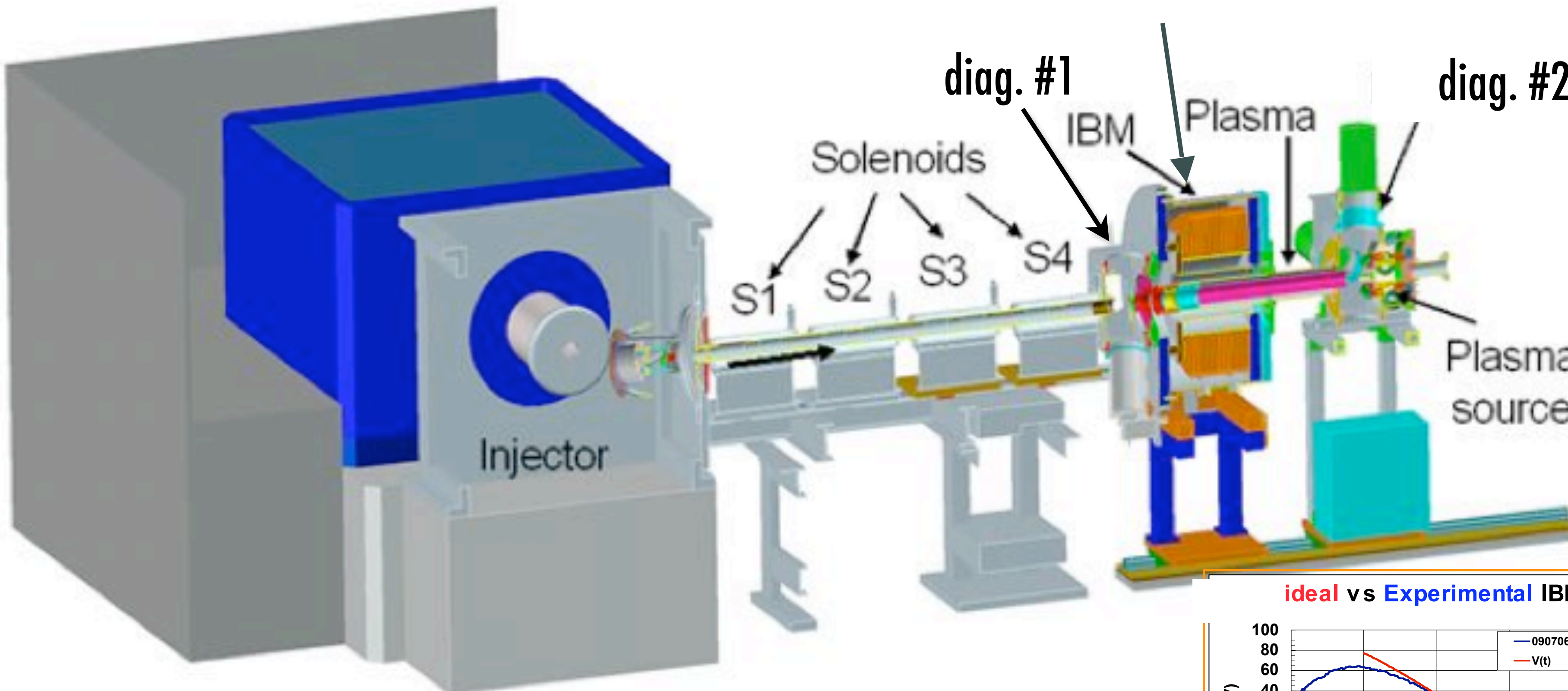
Low energy ion driver experiment: simultaneous transverse focusing and longitudinal compression

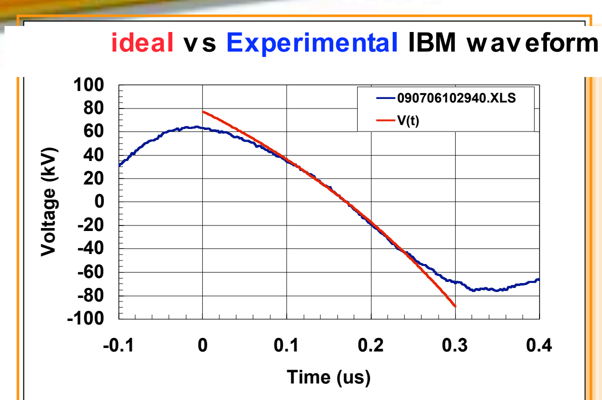
P. Seidel, et al, APS DPP 2007

E_i = 0.3 MeV K^+

I_i = 25 mA

IBM =Induction bunching module

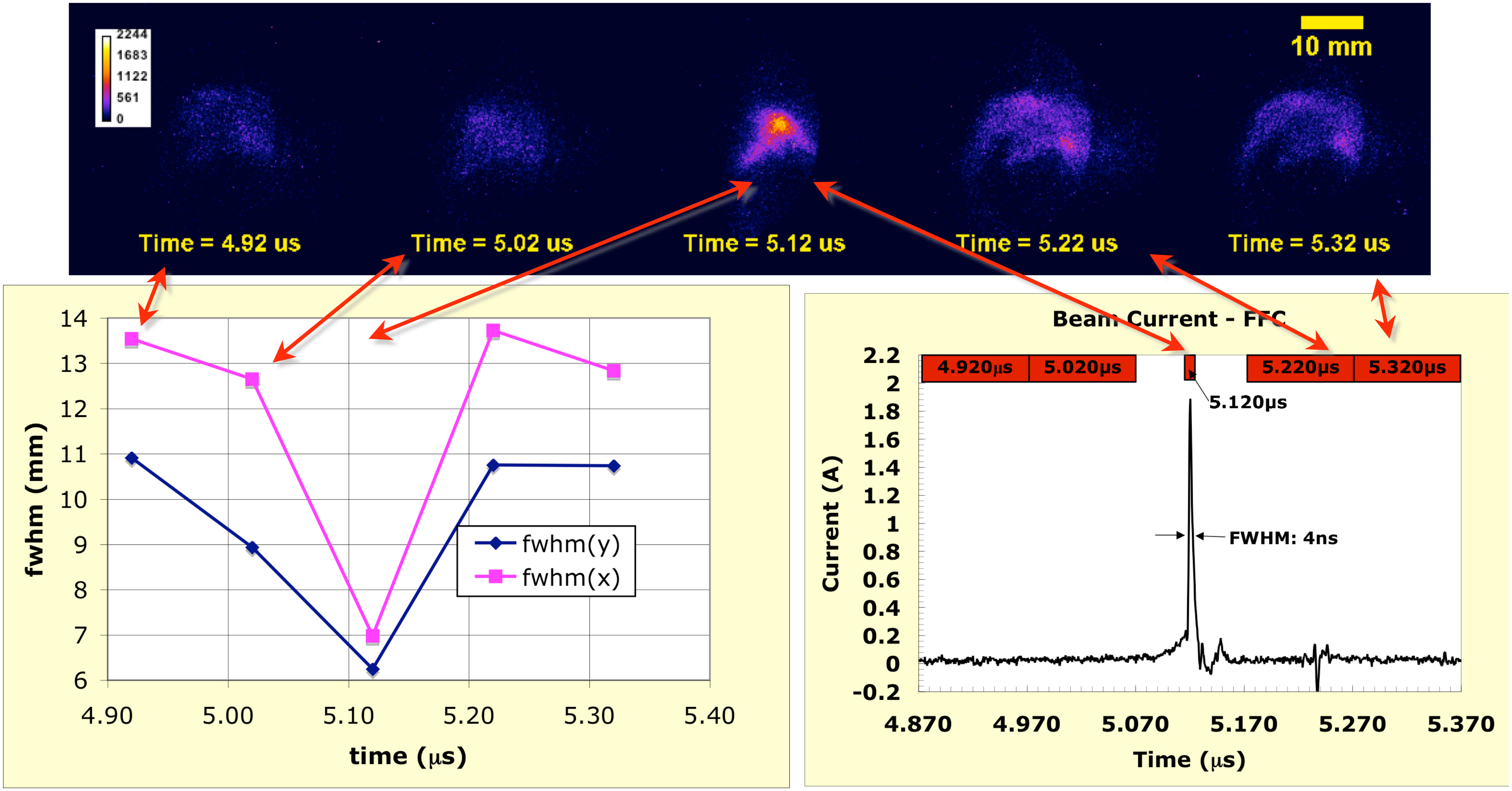




Objectives: Preservation of low emittance, plasma column with $n_p > n_b$,
($n_{b\text{-init}} \approx 10^9$ /cm^3,
$n_{bmax} \approx 10^{12}$ /cm^3 now, later, $\approx 10^{13}$ /cm^3)

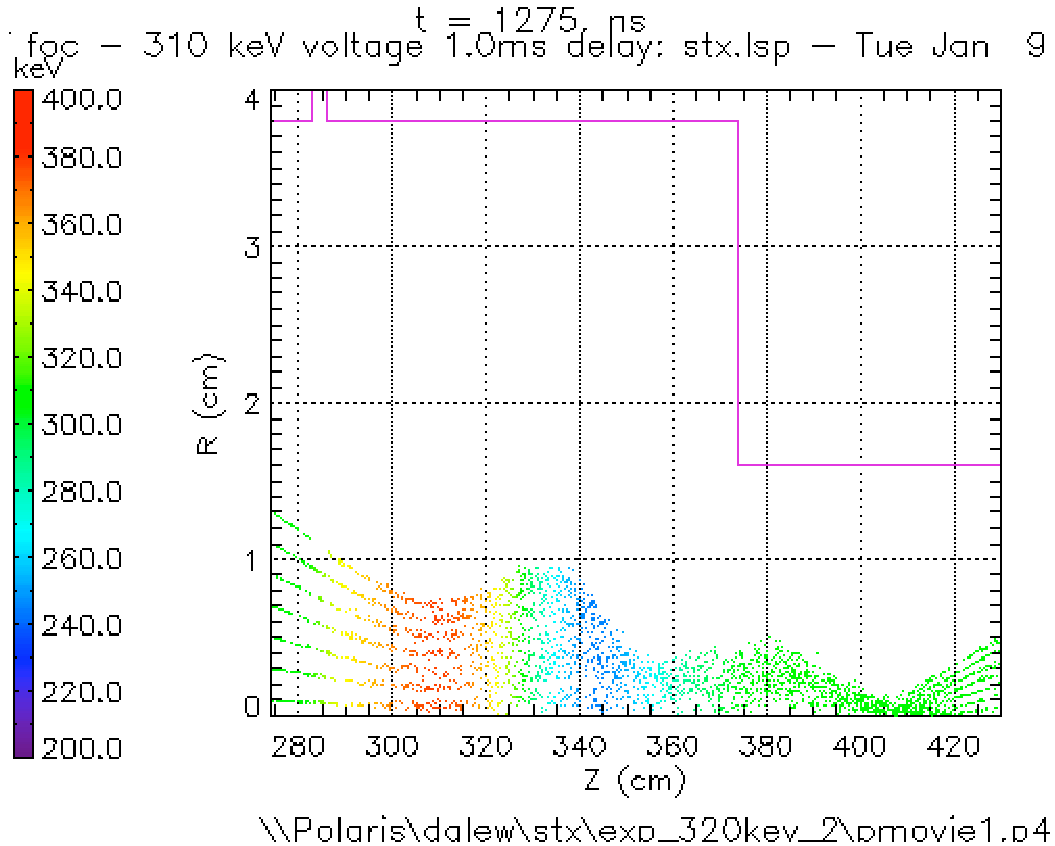
Minimum spot size @ same time as peak compression

P. Seidel, et al, APS DPP 2007



2X reduction in the spot size (4X increase in beam intensity) brings the peak beam density to the range $n_b \approx 10$ 10^{12} cm^{-3}.

LSP simulation (Welch, et al, 2007) of pulse compression on NDCX-1



Ion driver parameters

Table 1. Neon beam: Z=10, A=20.17, E_{min}=7.7 MeV, E_{center}=12.1 MeV, E_{max}=20.1 MeV, and Δz_{min}=40 μ.

ρ(g/cm^3)(% solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (μ)	480			48			4.8		
kT (eV)	**3.1**	**4.8**	**15**	**4.2**	**7.3**	**18**	**5.9**	**12**	**22**
Z*	1.1	2.1	2.7	0.56	1.7	2.6	0.56	1.2	2.5
$\Gamma_{ii}=Z^{*2}e^2n_i^{1/3}/kT$	0.45	1.1	0.95	0.30	0.63	1.4	0.30	0.70	1.6
$N_{beam}/(r_{spot}/1mm)^2/10^{12}$	1	3	10	1	3	10	1	3	10
Δt (ns)	84	48	27	3.8	2.2	1.2	0.04	0.03	.014
U (J/m^3)/10^{11}	.015	.045	0.15	0.15	0.45	1.5	1.5	4.5	15

Barnard et al, PAC 2005

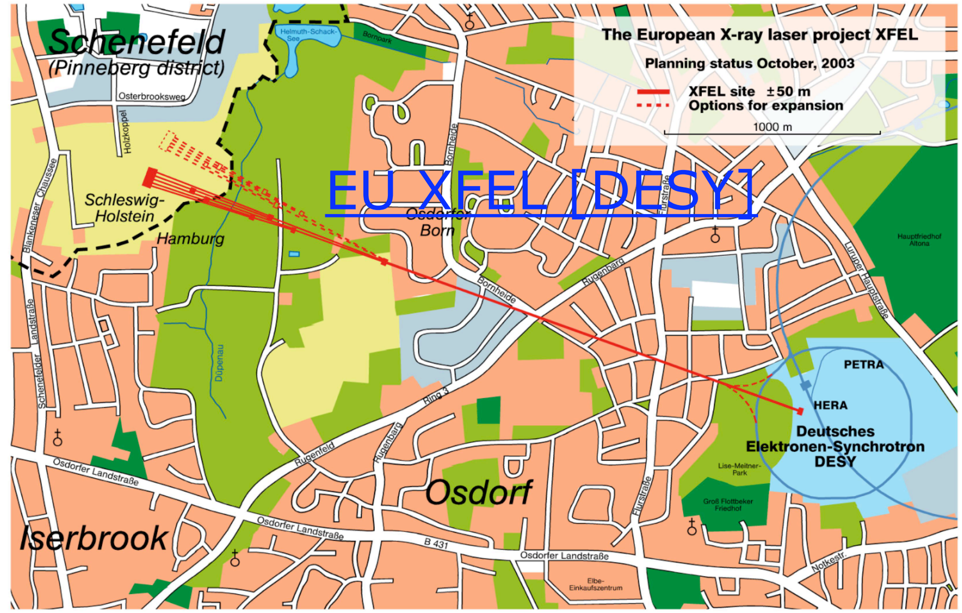
More parameters later today, esp. for ring geometry (Tahir)

X-ray Free electron lasers

- ‘Bulk’ heating of matter with fs-ps x-rays pulses
- High intensity pulses driven by GeV electron beams
- FEL requires intense electron beam. Charged particle beams tend to self-destruct.

X-ray sources expand

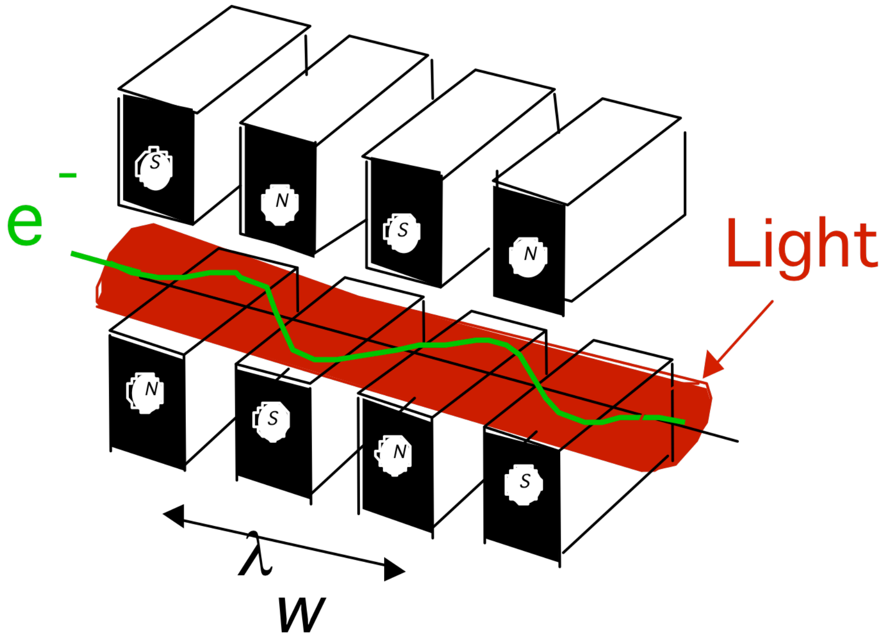
Fig. 2 Proposed site for XFEL machine at SPring-8.



LCLS [SLAC] FEL

Current	~3.5kA
Energy	~15GeV
Beam radius	~30microns
X-Ray Energy/pulse	~2.5mJ
Repetition rate	~120Hz

X-ray Free Electron Laser

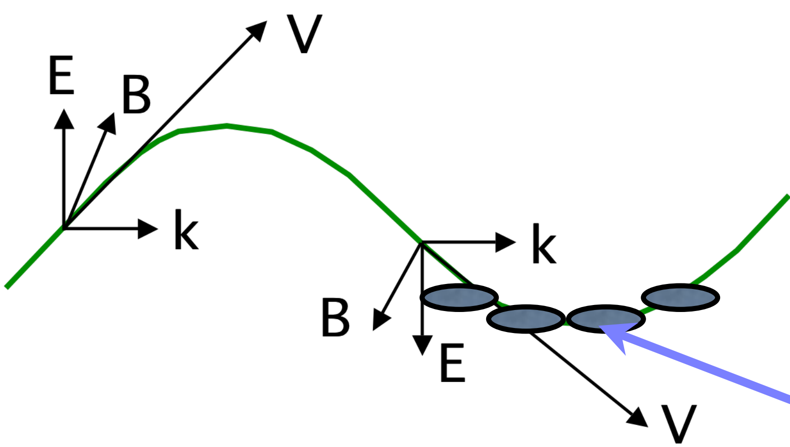


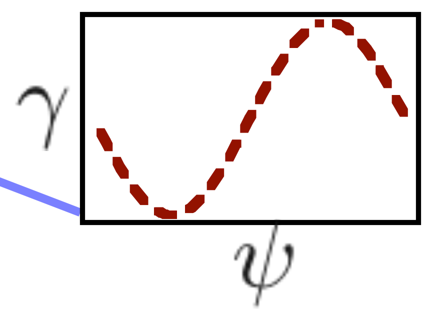
$$\frac{d\gamma}{dz} = \frac{q\vec{E}\cdot\vec{v}}{mc^2 v_z}$$

$$\psi = (k_s + k_w)z - \omega_s t$$

$$v_z = \frac{\omega_s}{k_s + k_w}$$

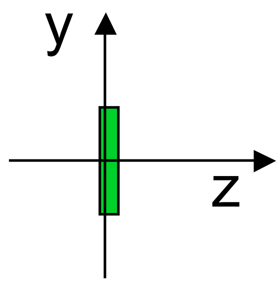
$$\boxed{\lambda_s = \lambda_w \frac{1+\gamma^2\beta_\perp^2}{2\gamma^2}}$$

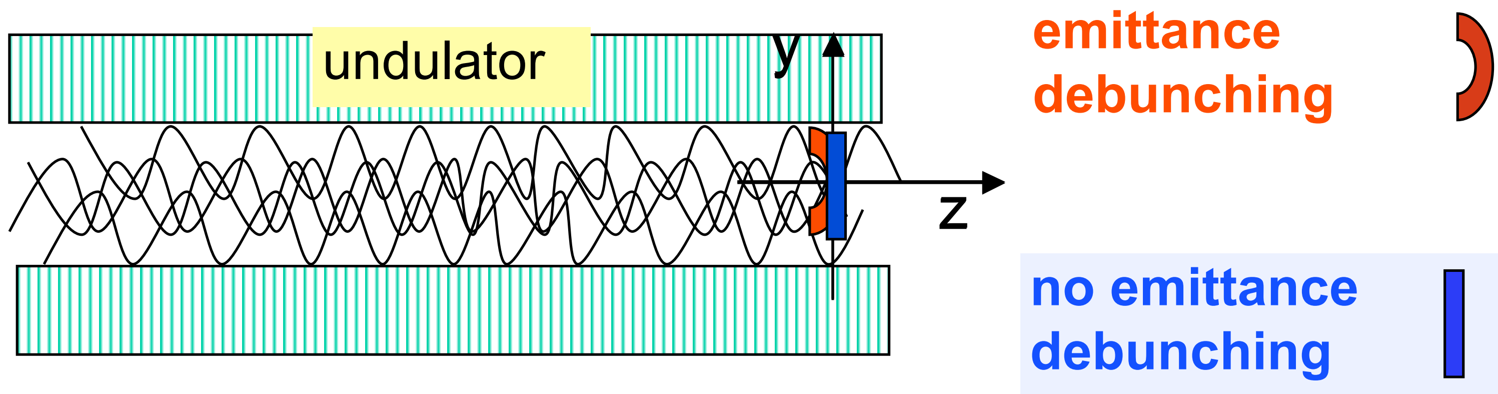


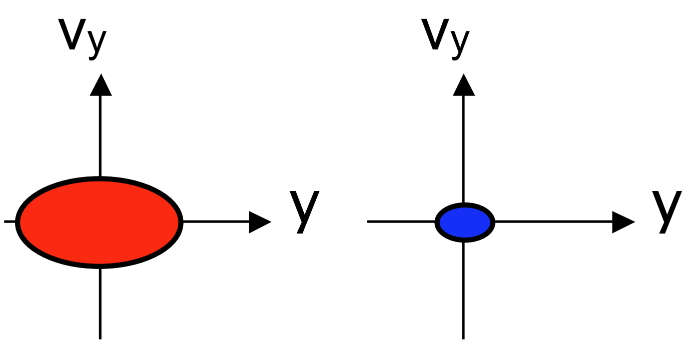


FEL unstable when all electrons have initially ~same parallel velocity

Transverse oscillations mess this up.





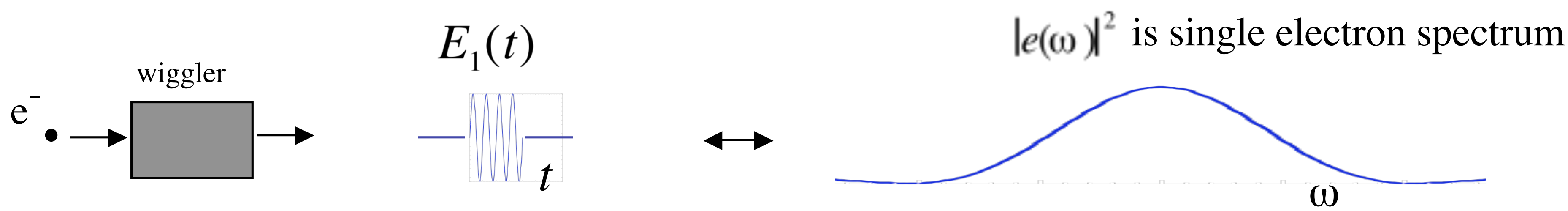


$$\frac{d\psi}{dz} = 2k_w \frac{\gamma - \gamma_r}{\gamma_r} \underbrace{+\kappa J_\perp}_{\text{emittance term}}$$

- Emittance requirement in FEL is hard to satisify at short wavelengths

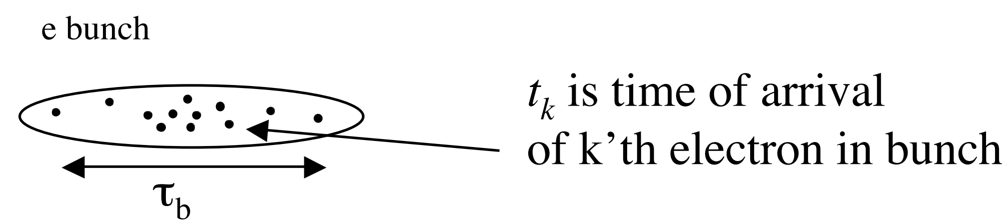
We are limited by our inability to make high quality beams

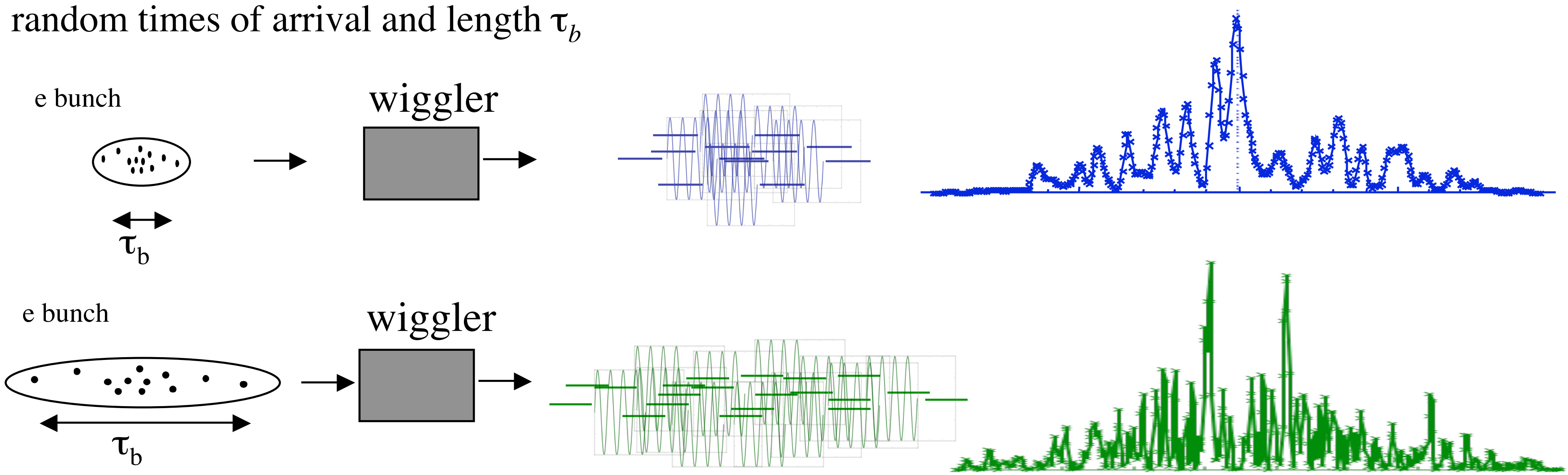
Single shot noise spectrum contains spikes of width $1/\tau_b$



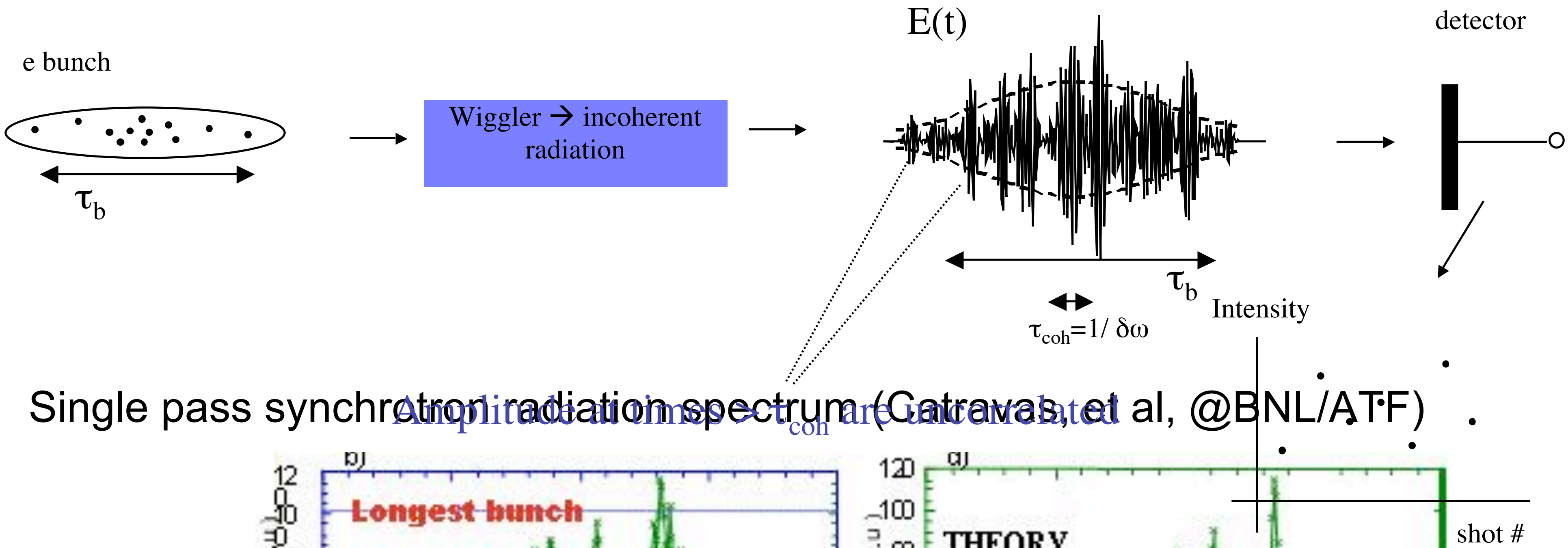
$$E(\omega) = e(\omega)\sum_{k=1}^{Nb} \exp(i\omega t_k)$$

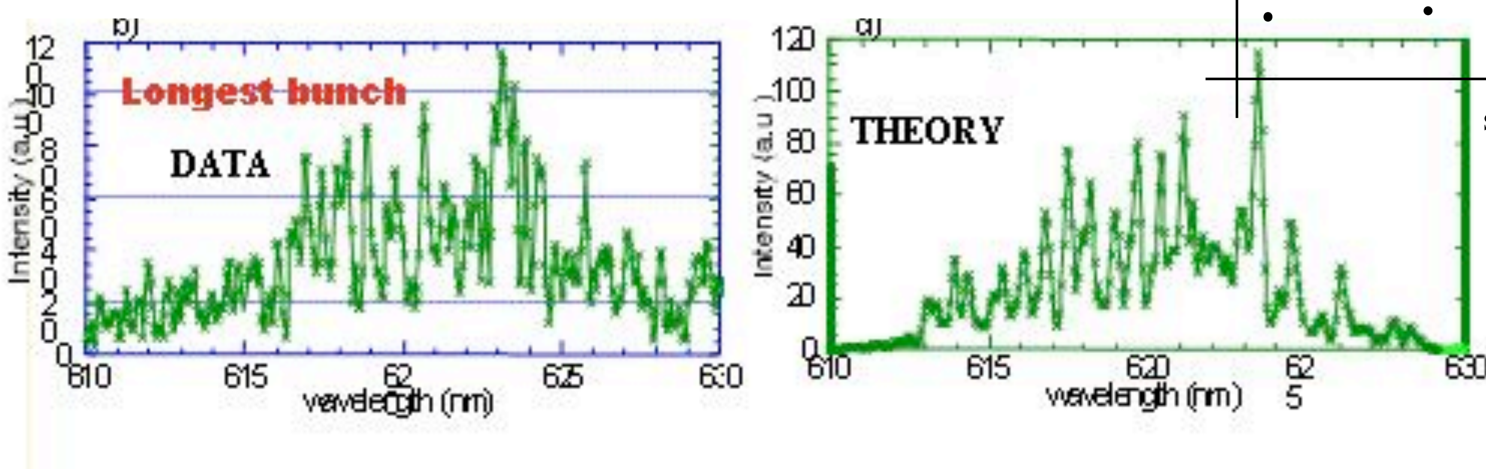
spectrum of electron bunch having random times of arrival and length τ_b





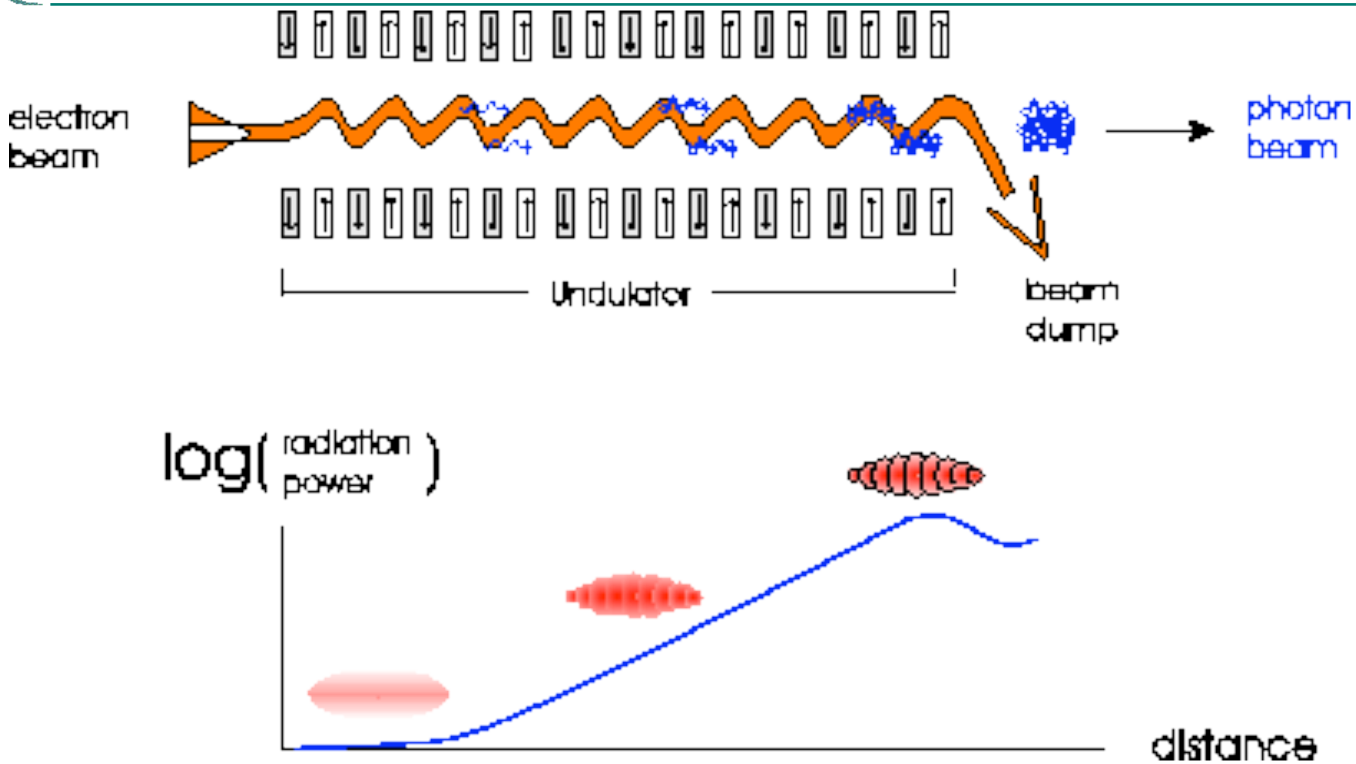
Single pass synchrotron radiation spectrum (Catravas, et al, @BNL/ATF)





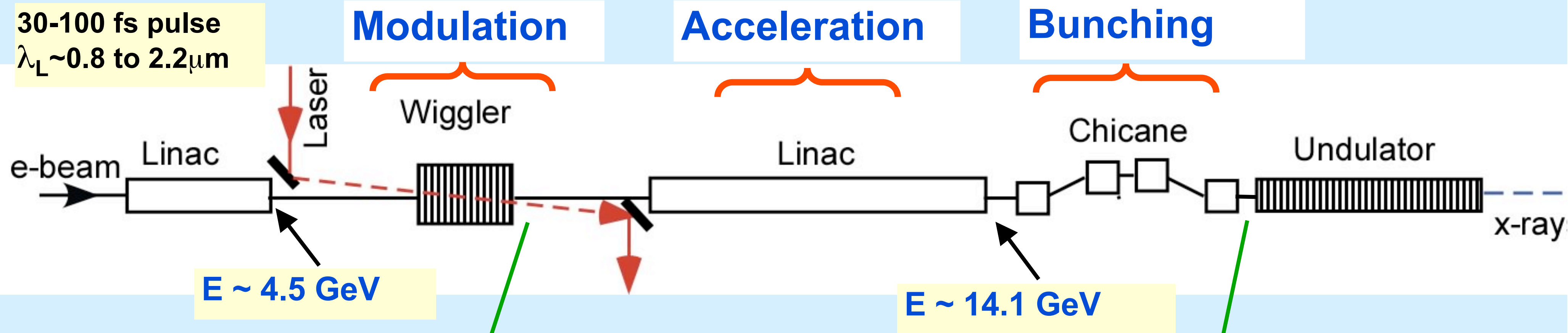
This is the spectrum from which SASE starts---with obvious noise issues and timing jitter.

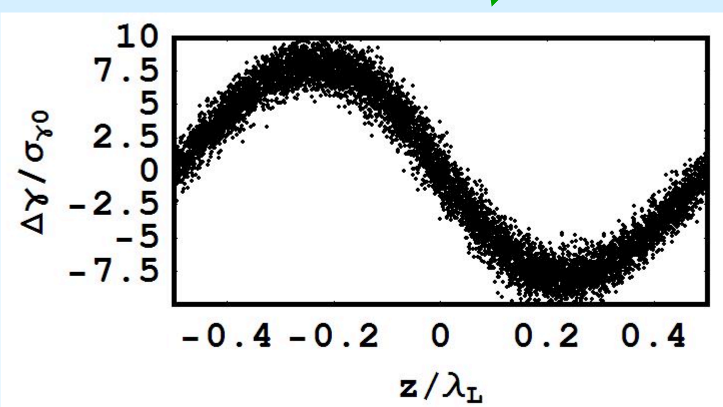
SASE FEL: amplification of fluctuations



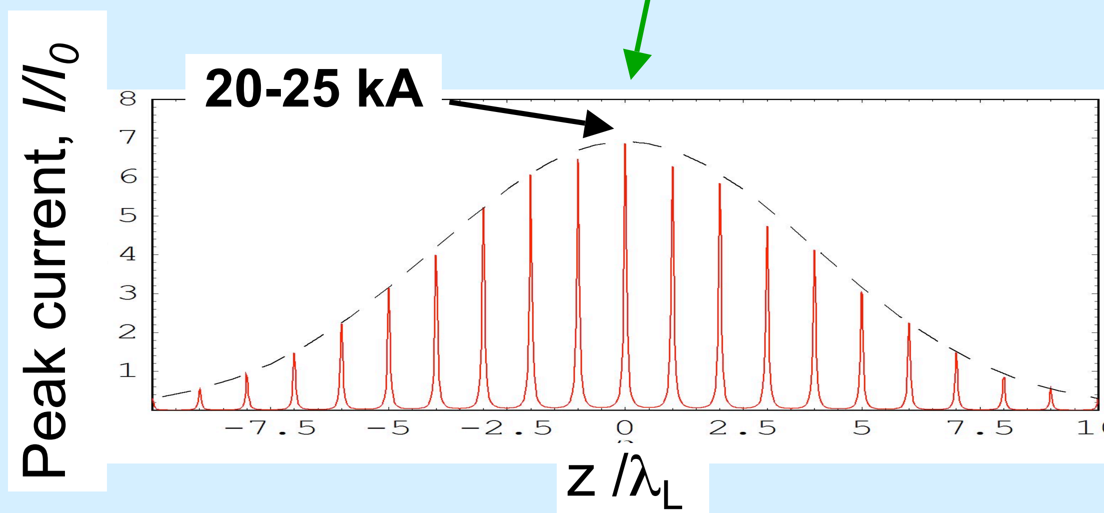
SASE spectrum and temporal shape has spikes--
poor longitudinal coherence

ESASE - Enhanced Self Amplified Spontaneous Emission FEL





One optical cycle

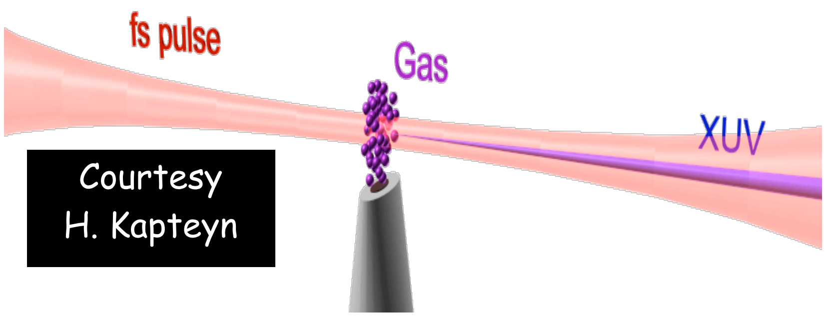


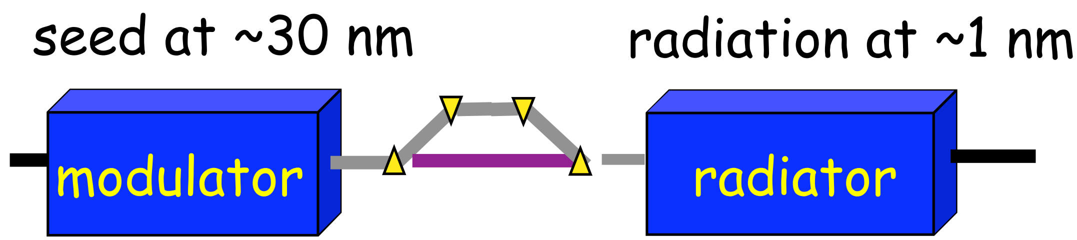
- Laser peak power ~ 10 GW ("easy")
- Short wiggler, ~ 10 periods

Electron beam after dispersive bunching

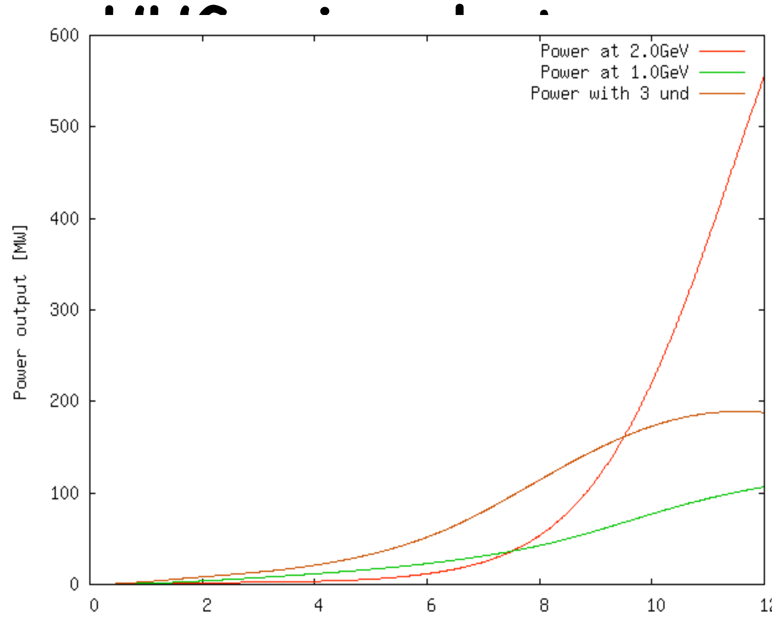
Laser-plasma soft x-ray seed for FEL

- **Reduce undulator length by seeding at short wavelength, using fewer stages of harmonic generation in the FEL**

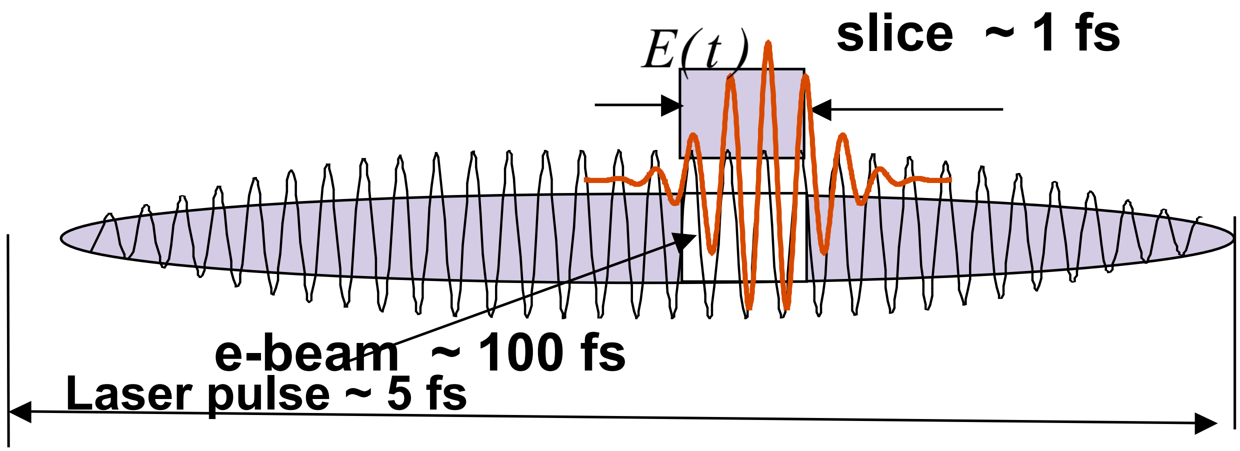




HHG in gas filled capillary producing seed pulse for energy modulation of electrons



Lasers manipulate longitudinal phase space during interaction in wiggler



Harmonic cascade seed

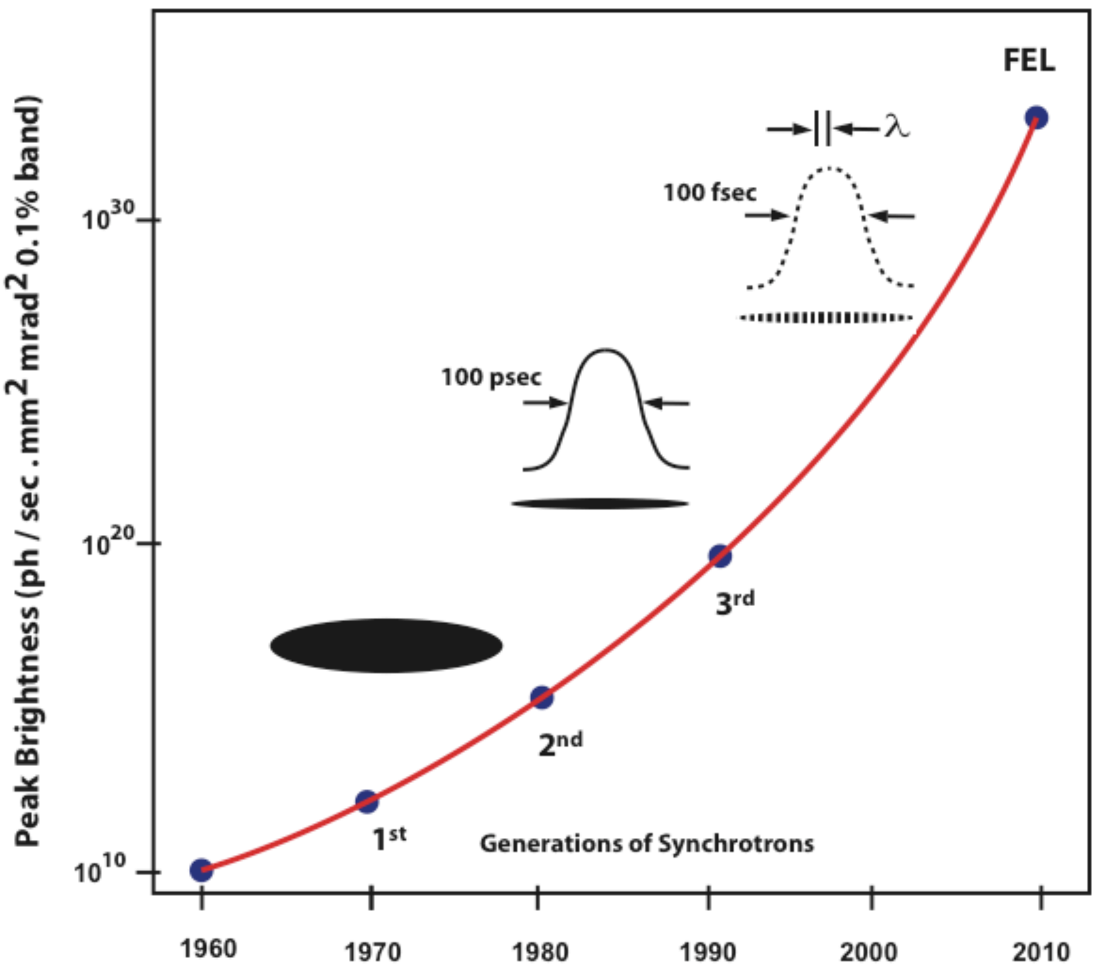
This cartoon is realized by manipulation of beam phase space with short pulse lasers. The idea is to condition and select specific slices of electrons to radiate differently (in direction, frequency, intensity, *etc.). For synchrotron sources this has already been accomplished:* Zholents & Zoloterev (1996); Schoenlein, et al, 2000; Khan, Part. Acc. Conf. 2005. For FEL see Zholents et al (2003-2007)

Evolution of synchrotron radiation sources

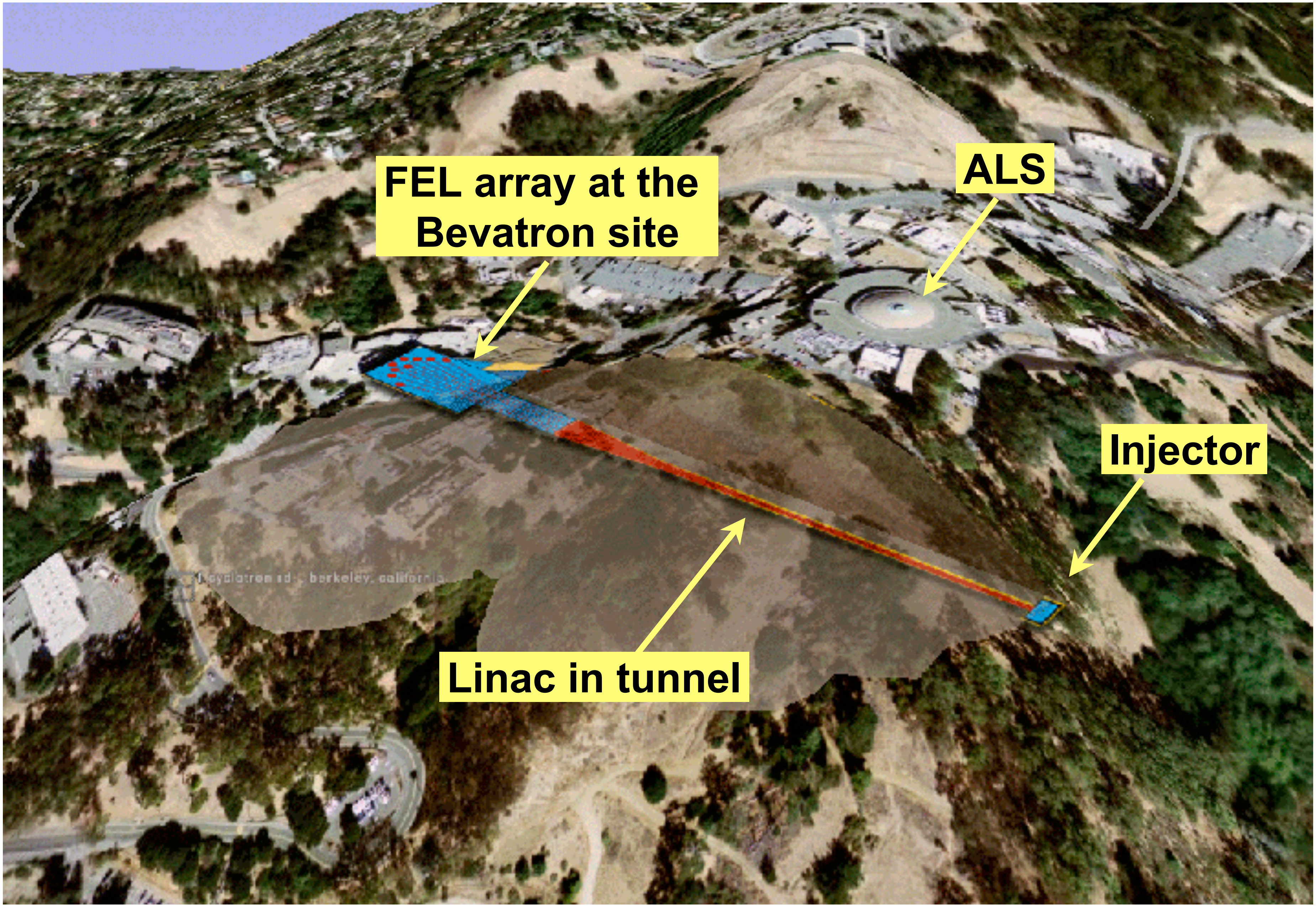
Future FELs may have

- Energy recovery (ERL)
- Superconducting RF
- High gradient RF
- Optical manipulation of phase space
- Harmonic cascades instead of SASE
- Beam Conditioning

- To achieve:
- High average flux
- High peak power
- Temporal coherence
- Spatial coherence
- Attosecond pulses
- Synchronization



Vision for a future LBNL light source



Summary: What drives X-ray FELs towards large energy electron beams?

1. Coherent emission--bunching at X-ray wavelengths

2. Limits on our ability to create and propagate high brightness electron beams

3. Limits on our ability to build short wavelength wigglers

Plasma-based Accelerators

- Electron Beams
- Ion Beams

Facilitated by the enormous progress in laser performance

Advantages: compact, synchronized to laser, short pulse

Disadvantages: hard to measure, jitter, energy spread,…

ION ENERGIES PRODUCED BY LASER GIANT PULSE

William I. Linlor[1]
Hughes Research Laboratories
Malibu, California

(Received 15 October 1963; in final form 19 November 1963)

Ion energies of ~1,000 eV have been produced by the action of a single "giant pulse" from a ruby laser.

The delivered energy was about 0.2 J in a pulse having full width at half maximum of about 40 nsec. The peak power was 5.4 MW, as measured with a Korad photodiode PDS-20-1C; all pulses were within 10% of this value. The area of the focal spot is not well known; approximate measurements indicate 10^{-3} cm^2. Energy was determined by the time of flight of the ions over a path of 4.3 cm, and ranged from 0.5 μsec for carbon to 1.2 μsec for lead.

The targets were in a system at 10^{-6} Torr prior to the laser burst. Within the vacuum system were mounted a lens of focal length 67 mm, a target plate on which the laser beam was focused, and a copper collector plate 3.1 cm o.d. with a 0.64 cm-diam hole to transmit the laser beam. Collector and target plate biases of −23 and −20 V added negligible energy to the ions in comparison with their thermal energy. As indicated in Fig. 1, resistors connected the collector and target to ground. The potentials

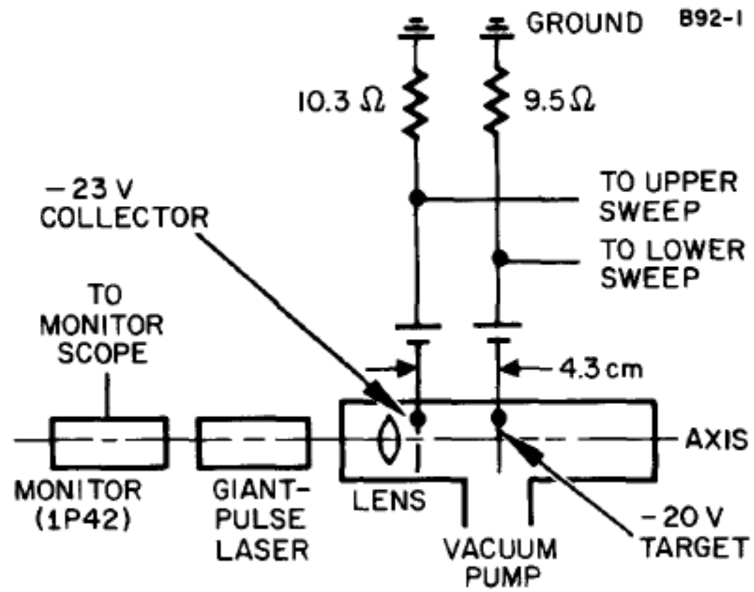
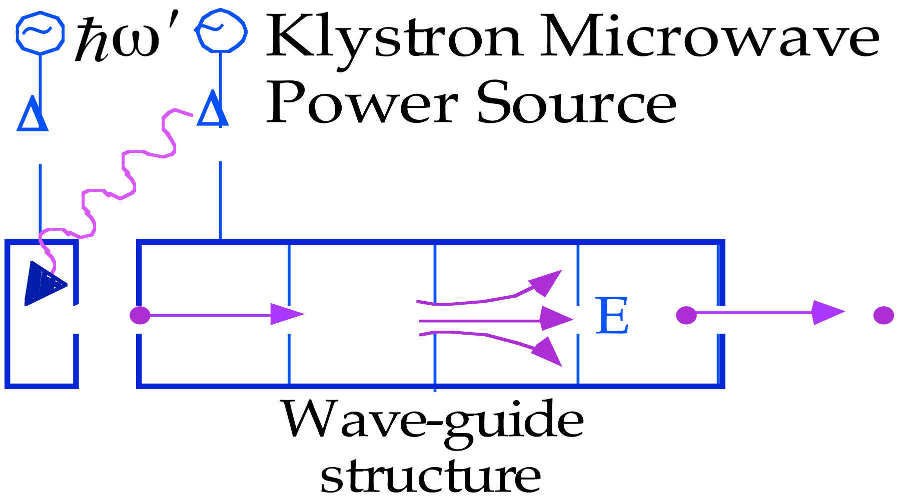


Fig. 1. Experimental system. Laser beam passed through hole in collector, and was focused on the target. Giant pulse was timed by monitor and by flow of electrons from target. System pressure before burst was 10^{-6} Torr.

Plasma-based Electron Linac



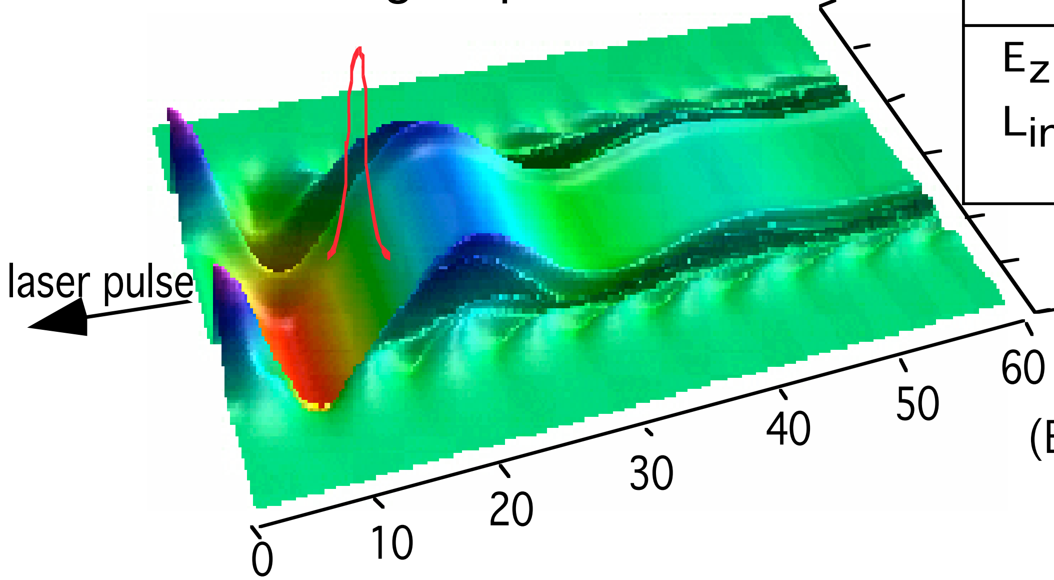
Conventional Linac

E_z : 10 - 200 MV/m

L_{int} : km's

$$W = e\, E_z\, L_{int}$$

Electron beam surfing on plasma electric field



(B. Shadwick, UCB/CBP)

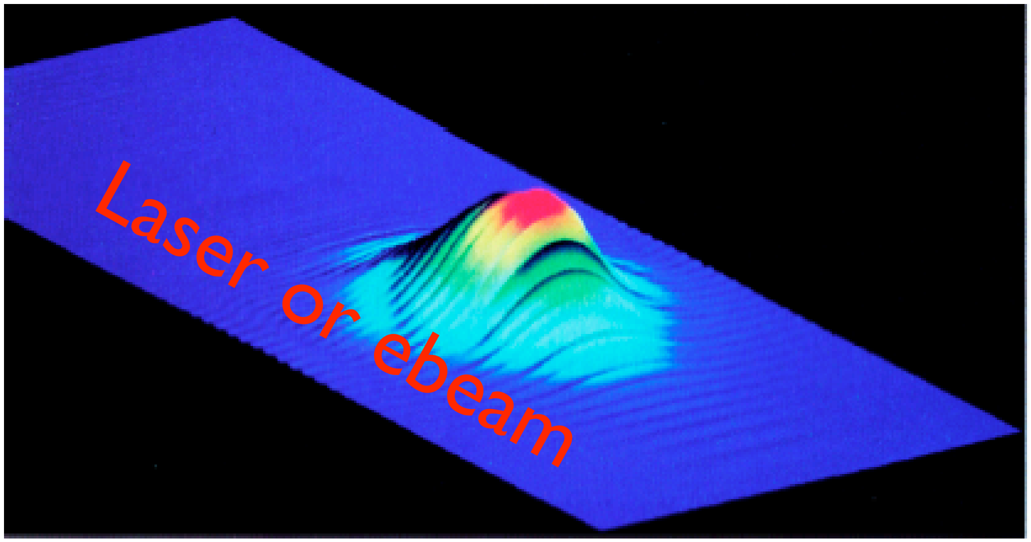
Laser driven plasma based linac

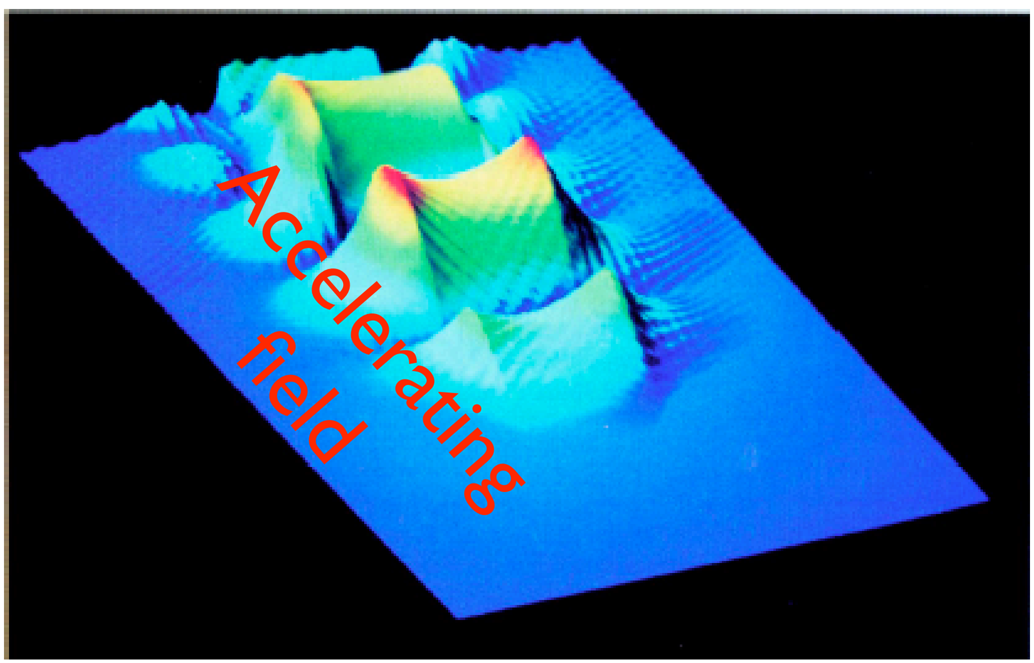
E_z : 10 - 100 GV/m

L_{int} : laser diffraction length

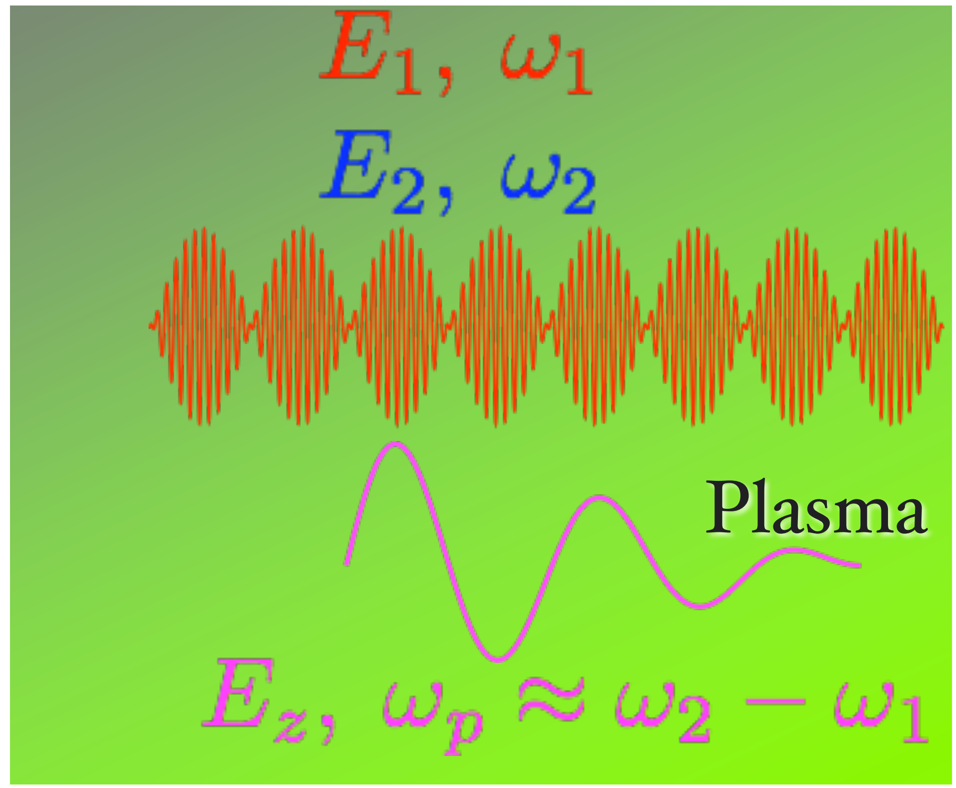
Creation of Accelerating Structures in Plasmas: Femtosecond Engineering

Wakefield

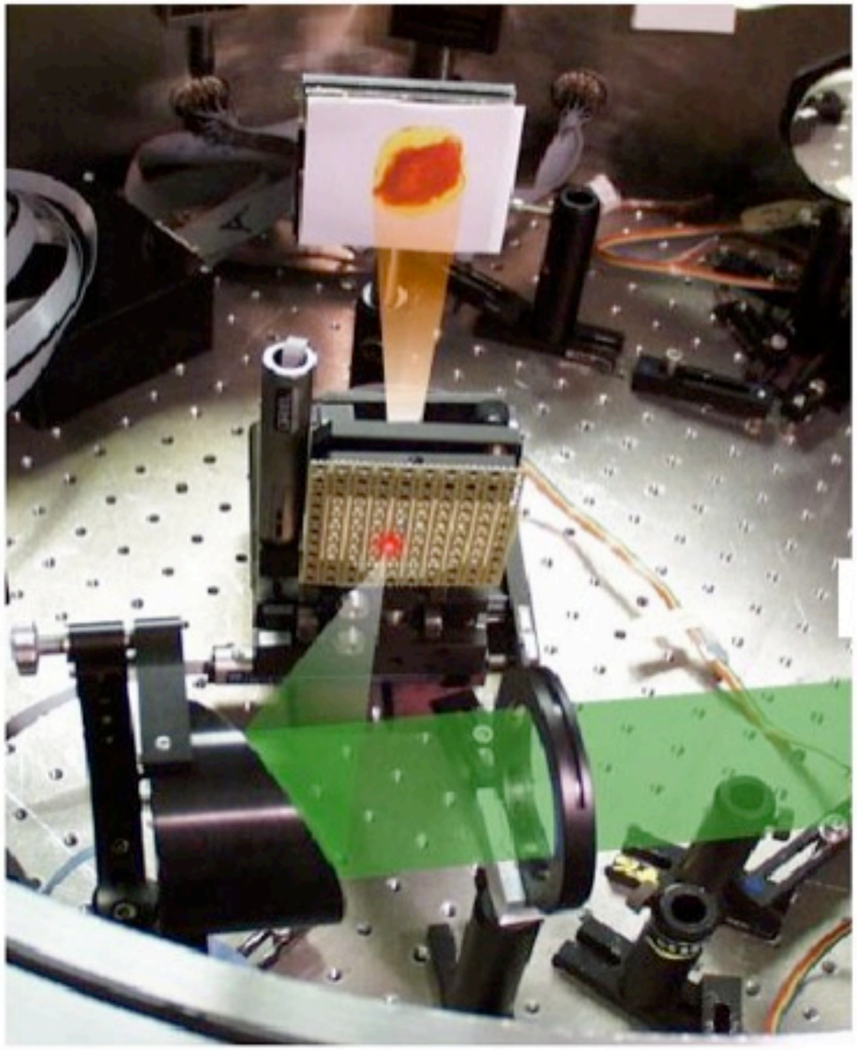




Beatwave



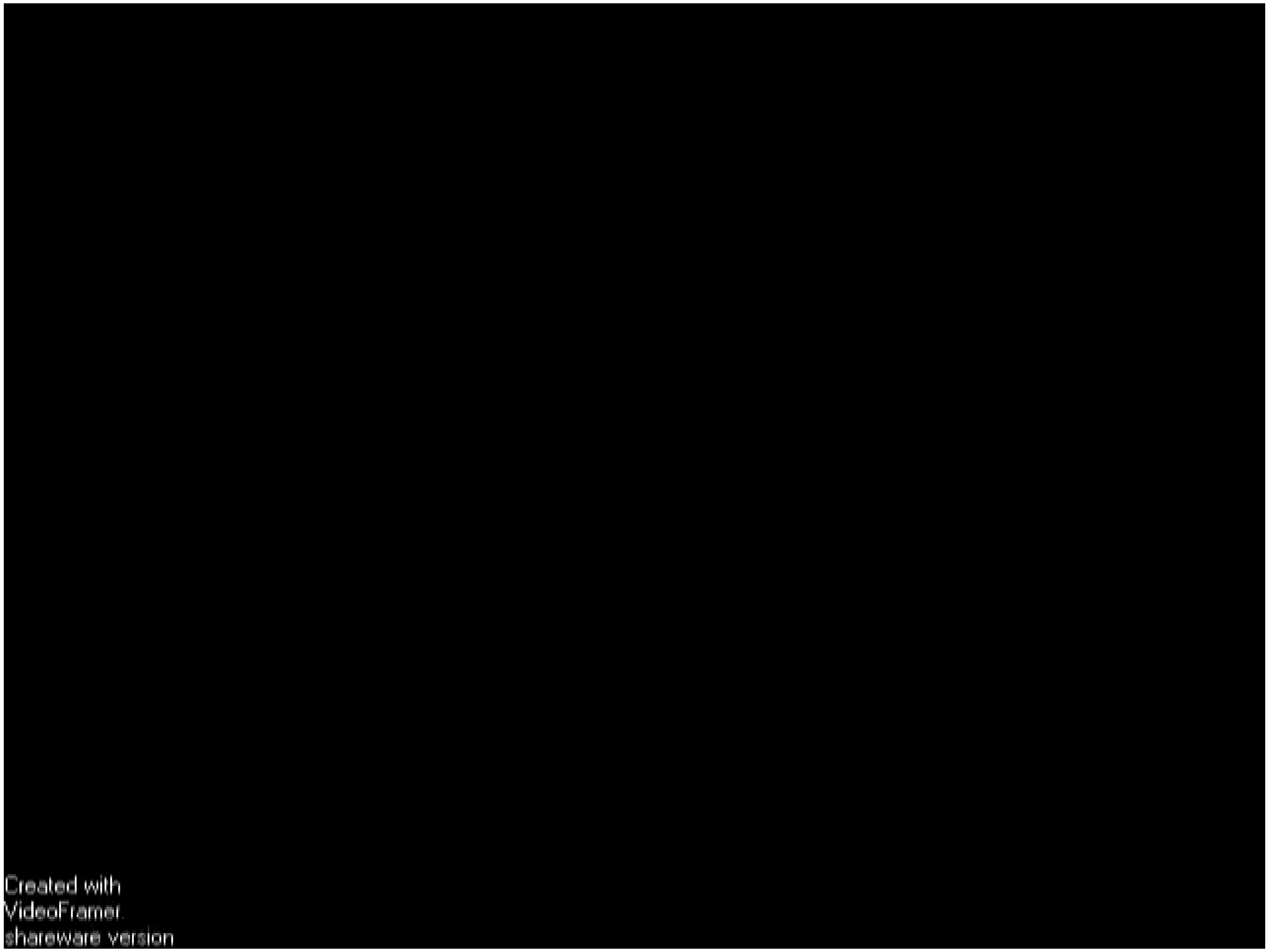
A Beam of MeV Protons



- $a_0 = 3.0$
- Cone angle = 40°
- Always normal to the target
- Front side origin
- 2π mm-mrad
- $E \sim 10$ GeV/cm
- $N > 10^{10}$ p
- $J = 10^8$ A/cm^2

A. Maksimchuk, K. Flippo, D. Umstadter, V.Y Bychenkov, *Phys. Rev. Lett.* **84**, 4108 (2000).

A laser-driven ion accelerator (cartoon)

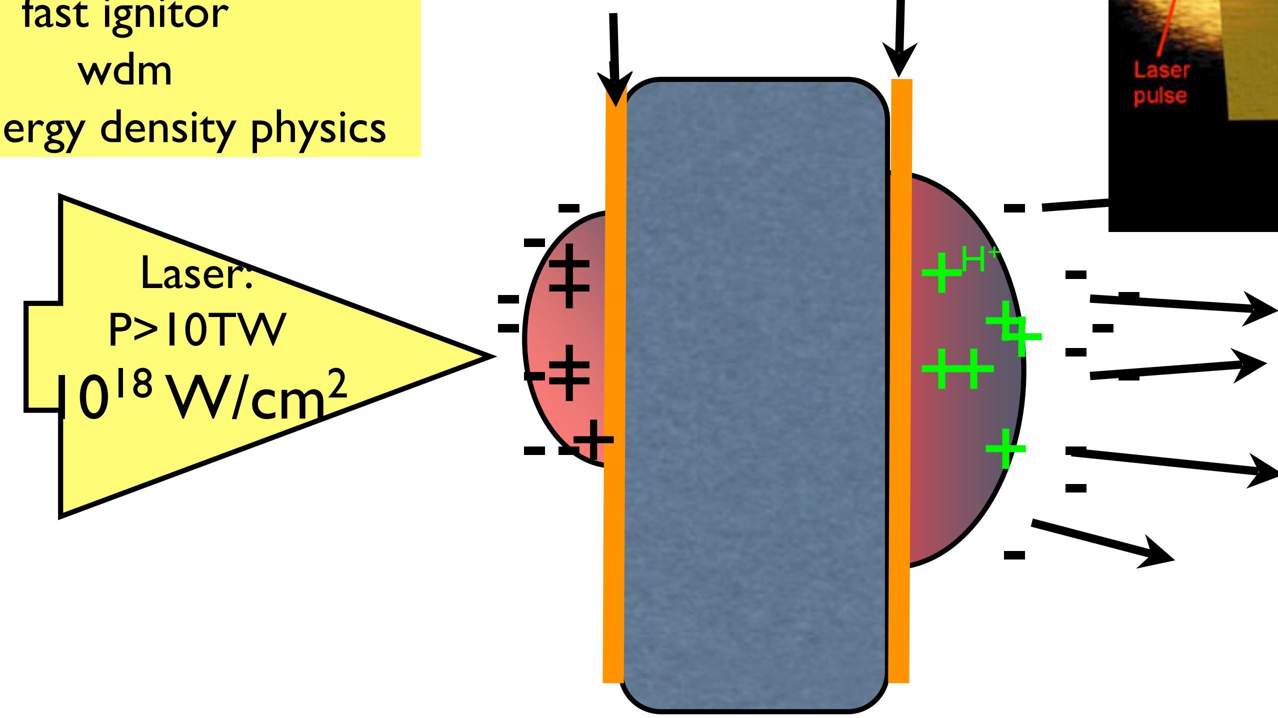


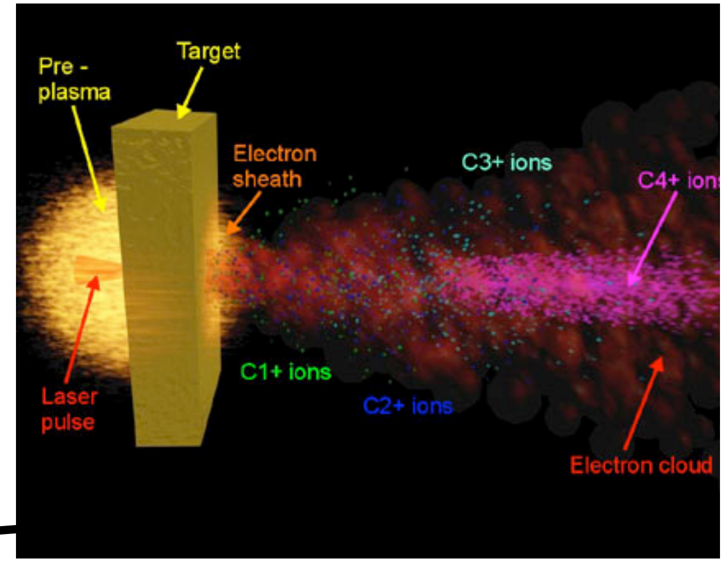
from supplementary material: B. M. Hegelich, B. J. Albright, J. Cobble, K. Flippo, S. Letzring, M. Paffett, H. Ru
Nature **439**, 441-444 (26 January 2006)

Ion Acceleration from laser-solid

Applications
Spallation source
plasma probe
fast ignitor
wdm
high energy density physics

Contaminants (H2O)
Surface prep





Heglich et al
Nature 2006

Properly prepared and shaped target can accelerate ions

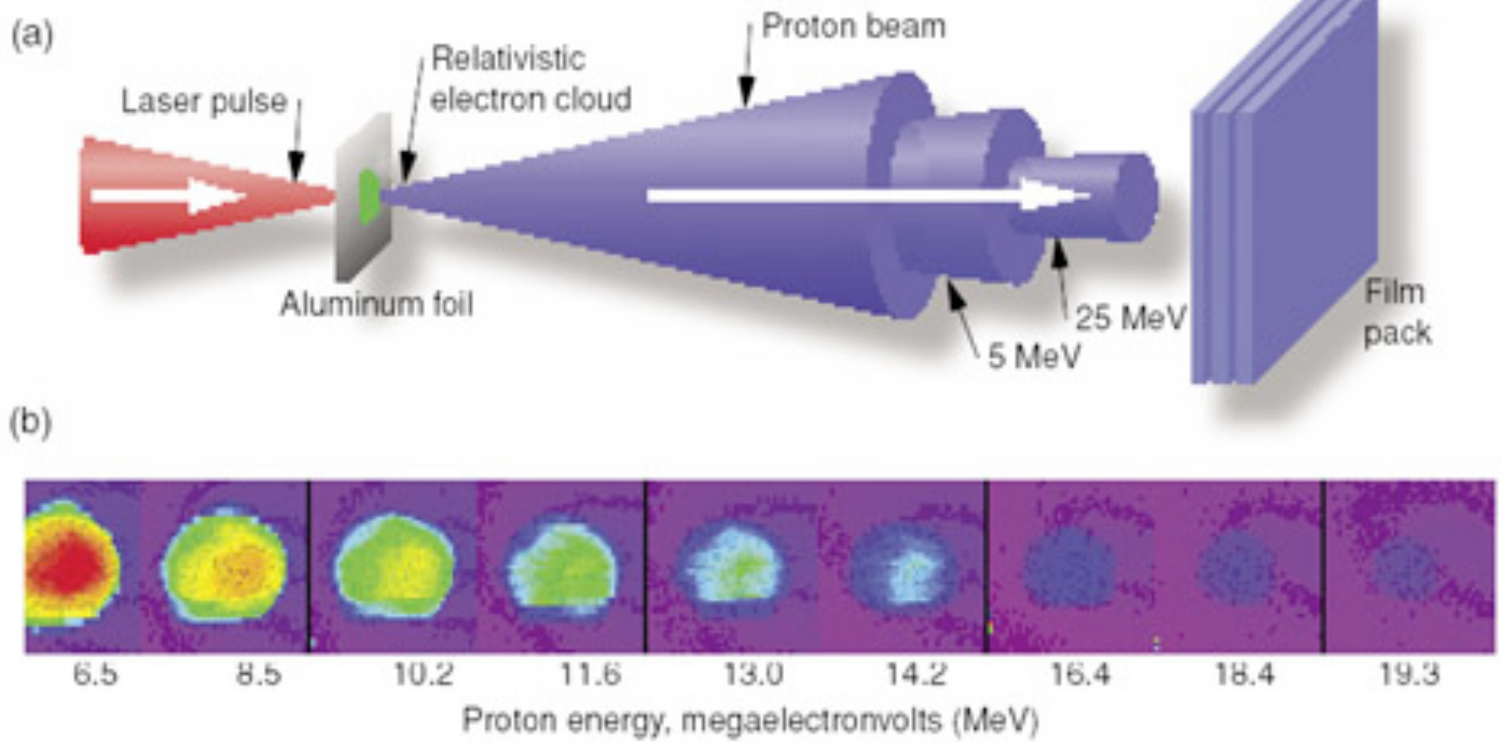
Gitomer et al, 1986

Sentoku et al. (2003)
Hegelich et al. (2002)

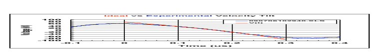
Snavely et al. (2000)
Fuchs et al 2005, Allen et al (2005)

Laser Acceleration of Ions

P. K. Patel, et al



- Protons from JanUSP --10J, 100fs
- High flux (1-2% of laser energy)
- Exponential distribution (kT~2-3MeV)
- High peak energy (<~25MeV)
- Strongly collimated (1-20)
- few ps pulse length



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Basic accelerator physics

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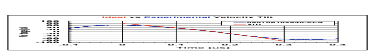

Conclusion

- Ion beams and FEL X-ray sources are being developed for, among others, warm dens matter applications
- Electron beams for X-ray FELs: high brightness and GeV energies--large facilities with CSR and other intensity limits
- Plasma acceleration-- 1-100GV/m fields, compact source, femtosecond bunch lengths, beam brightness, stability and dark current limits; high average and peak powers, cost,
- Ion acceleration-- high gradients, injector for conventional linac, WDM/HEDP/fast ignition/probing studies; no need for low beta rf structure; peak and average laser power, energy spread, emittance, staging, diagnostics for beam.
- MANY THINGS NOT DISCUSSED--but more on ION beam drivers in talks later today.